A GEOMETRIC APPROACH OF PASSIVE SHRIMP ESTIMATION

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ABSTRACT

Biological activity in the ocean is a significant source of ambient noise at higher frequencies. This paper demonstrates a passive technique of shrimp localisation and density estimation using the sharp clicks produced by shrimps. The estimation of the location and the density of shrimps find important application in fisheries. These pre-estimations give an idea about where to fish for the shrimps. Passive detection of shrimps can also be used to investigate the environment of the ocean, because the shrimps are dominant only at a particular area of the ocean.

Index Terms— Passive shrimp estimation, Localisation, Cross-correlation, Ocean Ambient Noise (OAN)

1. INTRODUCTION

The literature shows that there are a number of methods for estimating the location of the shrimps [1, 2, 3, 4, 5, 6]. The range and the bearing of the transient signals generated by the shrimps can be estimated using a linear array of hydrophones [4, 3]. However, this method of estimating shrimps requires that the array needs to be placed outside the shrimp dominated area, otherwise an ambiguity in the localisation arises. Another way of estimating shrimps is the image analysis [6] which is generally used in the estimation of the length of a shrimp and is not relevant here.

In this paper, a cross-correlation based shrimp detector is described which can be used anywhere in the shrimp dominated area and also does not use individual transient signal processing. A special type of hydrophone array is designed and tested to resolve the ambiguity in the location estimation.

Rest of the paper is organised as follows. Section two describes about the theoretical analysis of shrimp localisation and estimation. Sections three presents numerical simulation of passive shrimp estimation. Section four demonstrates experimental analysis and section five concludes the paper.

2. SHRIMP LOCALISATION AND DENSITY ESTIMATION

The cross-correlation between the shallow water ambient noise fields dominated by the sound of shrimps gives the estimation of the location a school of shrimps. The density of the shrimps in different areas of ocean bottom may also be estimated from the cross-correlation between shrimp dominated noise fields. If a school of shrimp is in α angle with hydrophone and horizontal axis, α can be estimated from the cross-correlation of sounds produced by shrimps and recorded using an array.

The figure 1 shows the geometry behind shrimp estimation.

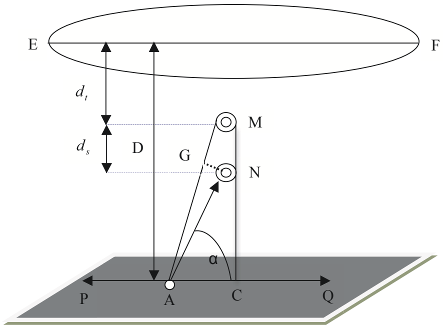

Fig. 1. Geometry of the shrimp localisation

In figure 1, A is the position of a shrimp on the seabed and M and N are the vertically separated hydrophones. When the shrimp makes a sound, the direct path signal reaches hydrophones, N and M following the AN and AM respectively. The shrimp is in α angle with the horizontal axis and hydrophone N. The delay difference between the direct paths at N and M is $GM = AM - AN$ where $AN = AG$. In figure 1, d_t, d_s and D are the distance of hydrophone M from

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the surface, separation between M and N, and the depth of the seabed respectively.

In figure 1, $\triangle ACN$ and $\triangle ACM$ are two right triangles. Therefore, according to Pythagoras theorem,

$$\begin{aligned} AM^2 &= AC^2 + CM^2 \\ \rightarrow (AN+GM)^2 &= AC^2 + CM^2 \ . \end{aligned} \quad (1)$$

In triangle $\triangle ACN$,

$$AC = \frac{CN}{\tan\alpha} \quad (2)$$

and

$$AN = \frac{CN}{\sin\alpha} \ . \quad (3)$$

Substituting AC and AN, the equation 1 can be expressed as

$$\begin{aligned} &(\frac{CN}{\sin\alpha} + GM)^2 = (\frac{CN}{\tan\alpha})^2 + CM^2 \\ &\rightarrow \frac{CN^2}{\sin^2\alpha} + 2\frac{CN.GM}{\sin\alpha} + GM^2 = CN^2.\cot^2\alpha + CM^2 \\ &\rightarrow \frac{CN^2}{\sin^2\alpha} + 2\frac{CN.GM}{\sin\alpha} + GM^2 = CN^2.(\mathrm{cosec}^2\alpha - 1) + CM^2 \\ &\rightarrow \frac{CN^2}{\sin^2\alpha} + 2\frac{CN.GM}{\sin\alpha} + GM^2 = \frac{CN^2}{\sin^2\alpha} - CN^2 + CM^2 \\ &\rightarrow 2\frac{CN.GM}{\sin\alpha} = CM^2 - CN^2 - GM^2 \\ &\rightarrow \sin\alpha = \frac{2.CN.GM}{CM^2 - CN^2 - GM^2} \ . \end{aligned} \quad (4)$$

Therefore,

$$\alpha = \sin^{-1}\frac{2.CN.GM}{CM^2 - CN^2 - GM^2} \quad (5)$$

where $CM = D - d_t$, $CN = D - d_t - d_s$ and GM is the path difference between the direct signals at two hydrophones denoted as Δd_{dd}. The values of CM and CN are available from the experimental geometry and the value of GM can be measured from the position of the correlation peak generated by the cross-correlation between the direct signals. The angle α calculated from equation 5 gives the location of the shrimp with respect to hydrophone N. The distance of the shrimp from the bottom end-fire region can also be calculated from equation 2.

A noise source from angle α always contributes to $\frac{\Delta d_{dd}}{c}$ away from the centre of the correlation. The strength of the correlation peak at $\frac{\Delta d_{dd}}{c}$ is related to the number of shrimps coming from the angle α. Therefore, the strength of the correlation peaks at position $\frac{\Delta d_{dd}}{c}$ helps to estimate density of the shrimps at α angle.

2.1. Ambiguity

The localisation technique using only two vertically separated hydrophones gives that the shrimps can be located in AC distance from the bottom end-fire region which results a circular area of radius AC. This circular range estimation only helps if the shrimps are uniformly distributed on the seabed. For the scatted distribution of the shrimps this cause ambiguity in the estimation of the exact position of the shrimps.

The correlation peaks generated by the cross-correlation between direct signals contribute in a range from the correlation centre to the travel time equivalent to the distance between two hydrophones. The travel time between two hydrophones is $\frac{d_s}{c}$ where c is the speed of sound in the water. For the purpose of discussion it is considered that the shrimps located at different positions contribute to N_b equally spaced bins in the cross-correlation between the direct signals. If the width of each correlation bin is denoted as W_b, the number of bins N_b can be expressed as

$$N_b = \frac{d_s}{c \times W_b}$$

where the minimum value of W_b can be $\frac{1}{f_s}$. For the wider correlation bin several narrow correlation bins can be integrated to a single bin.

To give an example of ambiguity, consider the following scenario: the spacing between the vertically separated hydrophones is 2 m; the correlation bins due to the cross-correlation between the direct signals are distributed from the centre of the correlation to the $\frac{2}{1500}$ s away from the centre; a bin width of $\frac{0.2}{1500}$ s is considered in the cross-correlation between direct signals for the ease of discussion which produces 10 correlation bins. Now using equation 5, the circular area of contribution to different correlation bin can be calculated.

The figure 2 shows the contribution of different areas to the different bins for the cross-correlation between direct signals at the vertically separated hydrophones in this scenario.

Figure 2 shows that there is a circular area of contribution for each correlation bin. That means the localisation using two vertical hydrophones cannot give the exact direction from where the sound of shrimps are coming.

2.2. Resolving ambiguity

The directional ambiguity can be resolved with a 4-hydrophone array as shown in Figure 3 which gives estimation of shrimp location without any ambiguity. In the array, hydrophone pairs (S_2, S_1), (S_2, S_3) and (S_2, S_4) are perpendicular on each other.

To illustrate the process of resolving ambiguity, the noise contribution from different areas to the correlation peaks for different pairs of hydrophones need to be analysed. To resolve the ambiguity, a unique area of contribution for different hydrophone pairs needs to be found.

In the case of horizontally separated hydrophones, the area of contribution follows a hyperbolic relationship for the cross-correlation between direct signals [7]. Figure 4 shows the conceptual diagram of the contribution of the noise

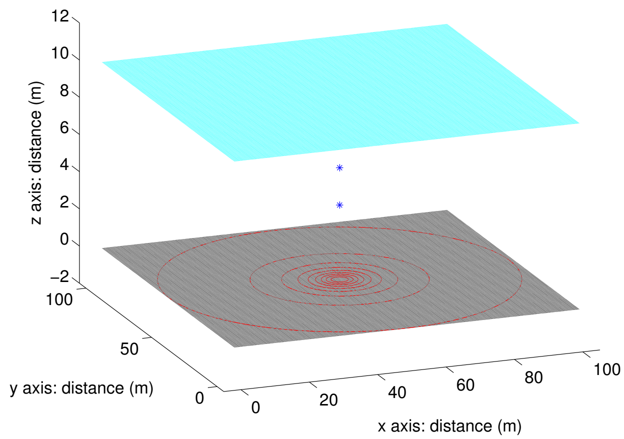


Fig. 2. The contributions from different areas to the correlation bins in the cross-correlation between direct signals for vertically spaced hydrophones

sources on a hyperbola to a correlation bin. In Figure 4, the hydrophones are placed at $B'(-a, 0, b)$ and $A'(a, 0, b)$.

For the contribution of any noise source $C(x, y, 0)$ on the hyperbola of figure 4 to the correlation bin $t = \frac{3a}{2c}$, the following condition needs to be satisfied.

$$B'C - A'C = ct$$

The condition can be expressed in the cartesian co-ordinate system as follows

$$\sqrt{(x+a)^2 + y^2 + b^2} - \sqrt{(x-a)^2 + y^2 + b^2} = ct$$
$$\Rightarrow x^2(\frac{4a^2}{c^2t^2} - 1) - y^2 = a^2(1 - \frac{c^2t^2}{4a^2}) + b^2 \ . \quad (6)$$

The area of contribution for two horizontal pairs of hydrophones, (S_2, S_3) and (S_2, S_4) are shown in Figure 5.

where c is the speed of sound. The area of contribution for vertical hydrophone pair (S_1, S_2) is already shown in Figure 2. The overlapped area of contribution of two horizontal and one verticals pairs of hydrophones are shown in Figure 6.

In Figure 6, each overlapped region contributes to a particular correlation bin of each pair of hydrophones which resolves the ambiguity in the estimation of the location of the shrimps.

2.3. Shrimp localisation steps

Shrimp localisation without ambiguity can be achieved experimentally using an array of four hydrophones as shown in figure 3. The steps of shrimp localisation are listed below:

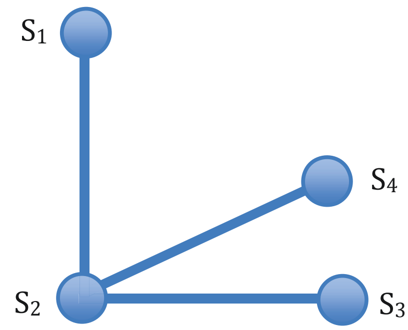


Fig. 3. A four-hydrophone array to resolve the ambiguity in the shrimp location estimation

1. A 4-hydrophone array shown in figure 3 is deployed underwater in the shrimp dominated area and the noise field is recorded simultaneously in the hydrophones of the array.

2. A band-pass (5-50kHz) filter is applied on the recorded noise fields to get rid of strong wind generated surface noise and low frequency shipping noises. The filtered noise field is also equalised to make the PSD flat.

3. Cross-correlation is performed between the filtered and equalised noise fields received at each pair of hydrophones.

4. The position of the strong correlation peak generated by the cross-correlation between the direct paths is measured from each of the cross-correlations.

5. Using the position of the correlation peak, the area of contribution for the vertical pair is estimated from equation 5, and the areas of contribution for both of the horizontal pairs are estimated from equation 6 as shown in figure 7.

6. The overlapped area of all these three areas of contribution for three different hydrophone pairs shown by an arrow in figure 7 is the estimated location of the most of the shrimps.

The resolution of the localisation depends on the number of bins in the cross-correlation. If the number of bins increases, resolution also increases. In the cross-correlation between the direct path and the surface reflected path, the number of bins is larger than the correlation between direct paths. This is because, in the cross-correlation between the direct and the surface reflected signals, the correlation peaks are generated in the range of the correlation centre to $\frac{2d_t + d_s}{c}$;

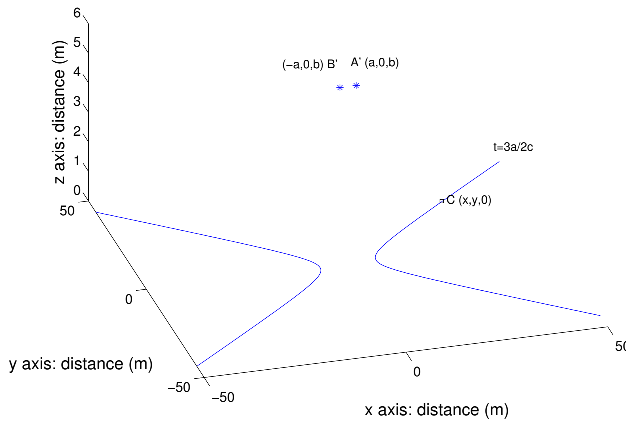


Fig. 4. Contribution of hyperbola to a particular bin when hydrophones are distance b above the noise plane

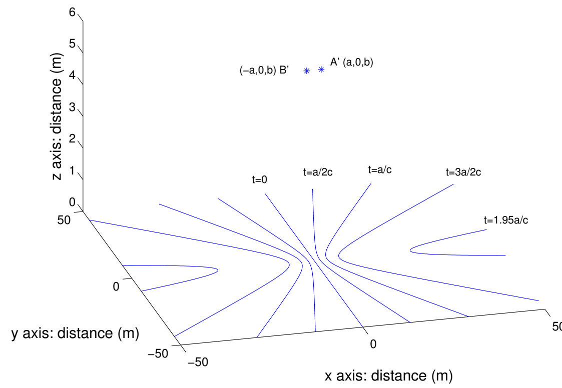
whereas in the cross-correlation between the direct signals, the peaks are generated in the range of correlation centre to $\frac{d_s}{c}$.

Therefore, localisation using the cross-correlation between the direct and surface reflected signal is expected to result an improved resolution over the correlation between direct signals, but it does not. The reason of this is that in the cross-correlation between the direct and the surface reflected signal, both the vertical and horizontal pair of hydrophones result very similar area of contribution to the correlation bins. Therefore, the directional ambiguity cannot be resolved.

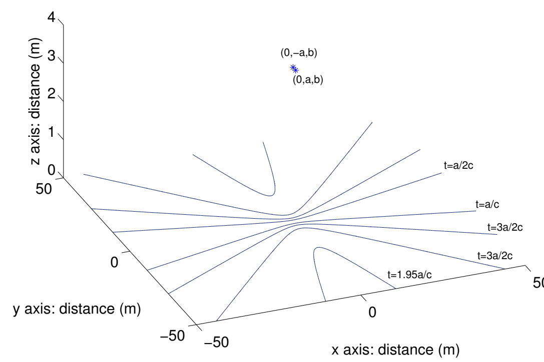
2.4. Shrimp density estimation

The density of the shrimps in a school of shrimps can be estimated from the strength of the peaks produced by the cross-correlation of the sounds generated by the shrimps. The strength of a correlation peak is directly proportional to the number of the shrimps contributing to that peak. The strengths of the peaks are also dependent on the distance between the hydrophone and the school of shrimp. Therefore, the attenuation due to the distance of the shrimps needs to be considered in the estimation of the density of the shrimps. So the strength of the peak as well as the location of the peaks must be used to estimate of the density of the shrimps in a particular school of shrimps.

The shrimp localisation procedure can be used to infer the distance of the shrimps from the array. The length of the direct paths at two hydrophones, S_1 and S_2 are denoted as d_{d1} and d_{d2} respectively. Therefore, the direct signals from the shrimp are attenuated by $\frac{1}{d_{d1}}$ and $\frac{1}{d_{d2}}$ respectively and correlation peak generated by the cross-correlation of these direct paths is attenuated by $\frac{1}{d_{d1}d_{d2}}$ due to spreading loss [8]. If the strength of the correlation peak is then normalised by $\frac{1}{d_{d1}d_{d2}}$, an idea about the number of shrimps contributing that particular peak is achieved which in turn gives the estimate of the density of the shrimps in a particular area.



(a)



(b)

Fig. 5. (a) and (b) represent area of contributions to different correlation bins for horizontal hydrophone pairs (S_2, S_3) and (S_2, S_4) respectively

Therefore, to estimate the density of the shrimps from the cross-correlation figure, the position Δd_{dd} for each correlation peak produced by the shrimps are measured from the correlation figure and the corresponding normalisation terms are calculated to make the strength of the correlation peak independent of the distance of the shrimps. Now comparing the strength of the correlation peaks after normalisation, relative density of the shrimps of different area can be achieved.

3. SIMULATION

A numerical simulation is performed to demonstrate the concept of estimating the position and the density of shrimp

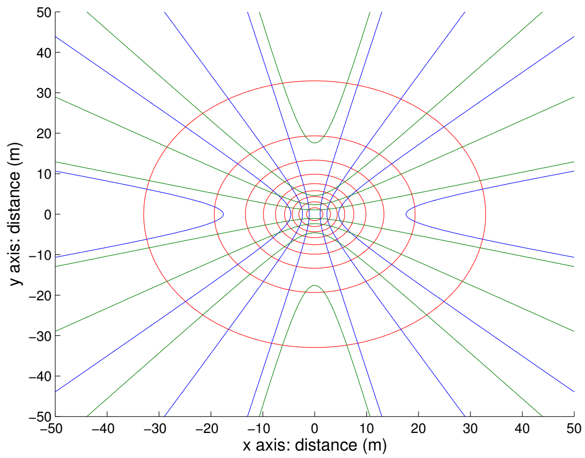


Fig. 6. Overlapping areas of the area of contribution for three pairs of hydrophones where blue, green line represent horizontal pairs and red line represent vertical pair

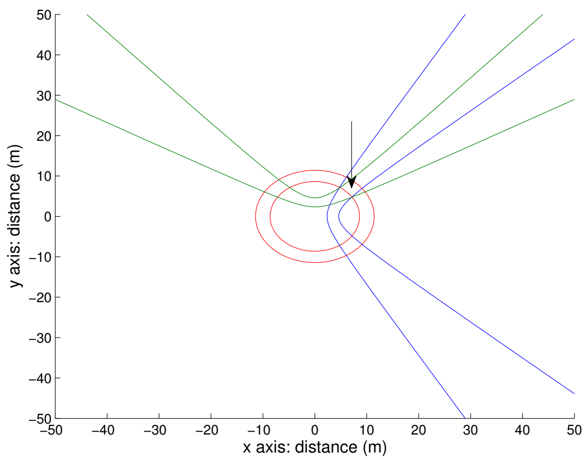


Fig. 7. Overlapped area of contribution for three different hydrophone pairs where blue, green line represent two horizontal hydrophone pairs and red line represent vertical hydrophone pair

schools. In the simulation, the depth of the seabed is set to 10 m and 1000 shrimps are assumed to be distributed in a group on the seabed. A 4-hydrophone array shown in figure 3 is used to record the shrimp noise where the vertical hydrophone pair is denoted as (S_1, S_2) and two horizontal hydrophone pairs is denoted as (S_2, S_3) and (S_2, S_4). The separation between the hydrophones of each pair is set to 2 m. The top hydrophone is placed at the depth of 4 m. Two sets of simulations are performed; one in which a shrimp school away from the end-fire region is considered and another in which the shrimp school is in the end-fire region. The shrimp and the hydrophone distributions considering a shrimp school away from the end-fire region are shown in Figure 8.

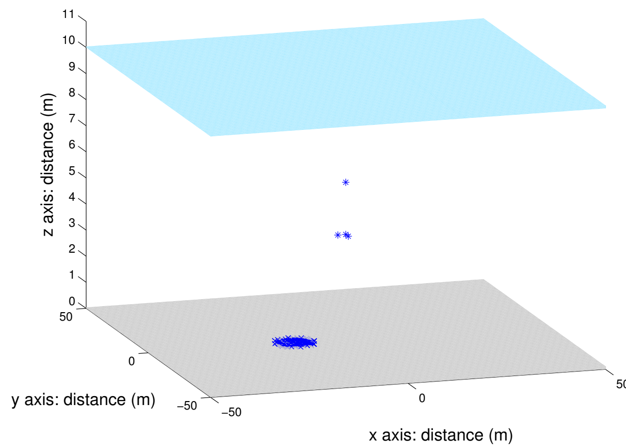


Fig. 8. Shrimp distribution: no shrimp school in the end-fire

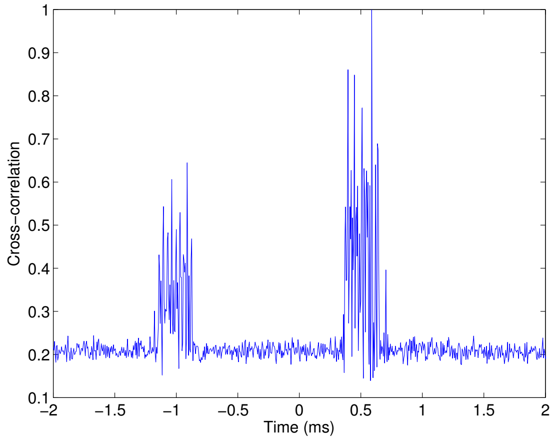
In figure 8, a total of 1000 shrimps are again grouped in a circular school of diameter 5 m, where the centre of the group is located at 13 m away from the end-fire region.

The cross-correlation between the noise fields recorded at two vertical hydrophones S_1 and S_2 is shown in figure 9(a).

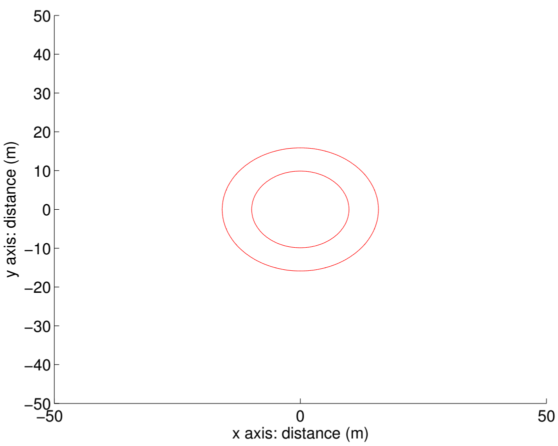
The cross-correlation between the direct paths of the shrimp sounds recorded at two vertical hydrophones S_1 and S_2 generates correlation peaks in the right side of the correlation centre. In figure 9(a), a group of peaks is generated centred at about 0.5 ms where two ends of the group are positioned at about 0.4 ms and 0.6 ms away in the right side from the correlation centre. The area of contribution corresponding to these two ends of the group of correlation peaks is shown in figure 9(b). The outer and the inner circle of figure 9(b) contribute to the correlation peaks at 0.4 ms and 0.6 ms of figure 9(a) respectively. The correlation peaks in between these two correlation peaks are contributed by the area in between the two circles of figure 9(b). The cross-correlation between two vertical hydrophones cannot identify in which part of the circular ring the school of shrimps is located.

To resolve the ambiguity, cross-correlations between direct signals received at two horizontal hydrophone pairs are considered. The cross-correlation between the direct signals at the horizontal hydrophones S_2 and S_3 along x axis is shown in figure 10(a).

In the cross-correlation, two groups of peaks are generated in the left side of the correlation centre where the strong group is generated by the cross-correlation between direct paths and the weak group is generated by the cross-correlation between surface reflected signals. Two ends of the strong

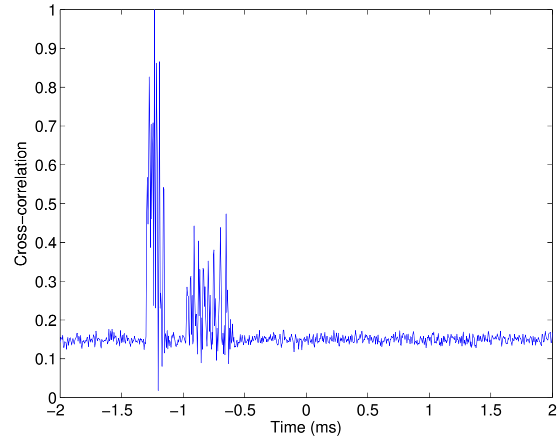


(a)

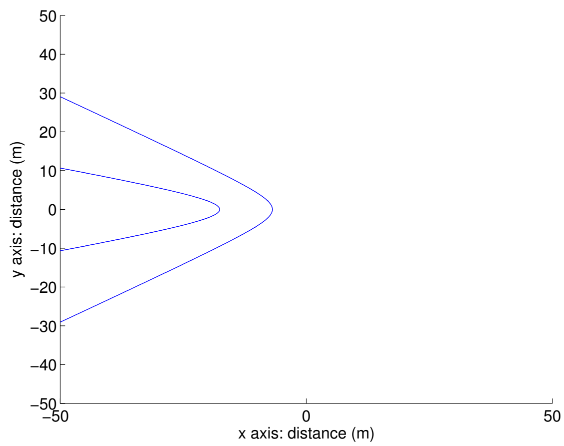


(b)

Fig. 9. (a) and (b) represent the cross-correlation of direct signals recorded at vertical hydrophones and the area of contribution to the correlation peaks respectively assuming no shrimp in the end-fire region



(a)



(b)

Fig. 10. (a) and (b) represent the cross-correlation of direct signals recorded at two horizontal hydrophones along x axis and the area of contribution to the correlation peaks respectively assuming no shrimp in the end-fire region

group are located at 1.15 ms and 1.3 ms away from the correlation centre. Using equation 6, the area from where the shrimps contribute to the correlation peaks at two ends of the group is shown in figure 10(b) that shows the hyperbolic area of contribution as expected.

Finally, the cross-correlation between the direct signals recorded at another two horizontal hydrophones S_2 and S_4 along y axis is shown in figure 11(a).

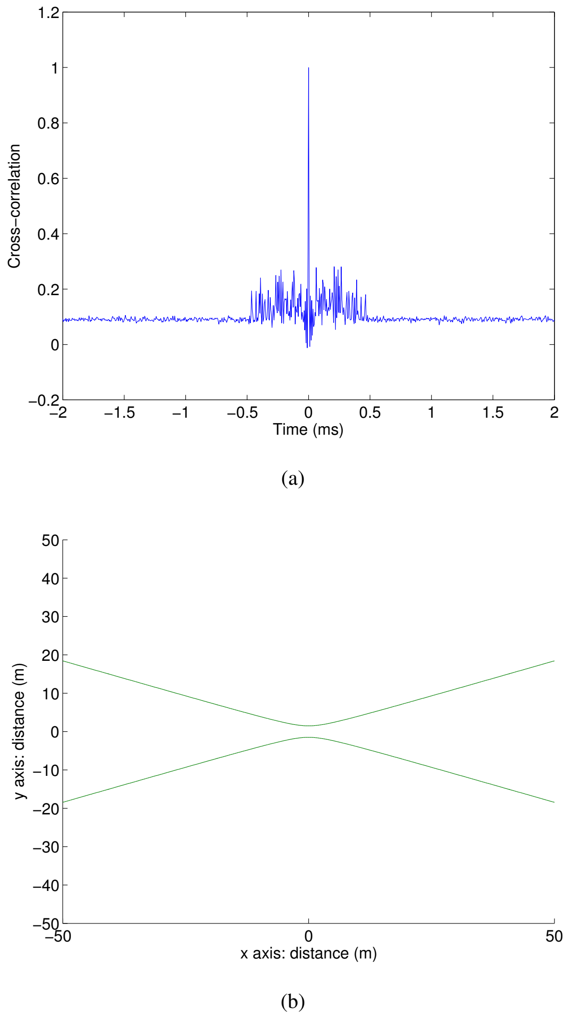
In figure 11(a), the correlation peaks at negative and positive sides are generated by the shrimps located at $y \leq 0$ and $y \geq 0$ respectively. Both of the positive and the negative end of the correlation peaks is located at 0.46 ms away from the correlation centre. Using these two correlation ends in equation 6, the contributing area to the correlation peaks of figure 11(a) is found and is shown in figure 11(b).

According to the theory, the common area of contribution of all the three hydrophone pairs gives the location of the shrimps as shown in figure 12.

The arrow indicated common area of contribution of one vertical and two horizontal pairs is centred at about 12.8 m away from the end-fire region on the negative x-axis which is in a good agreement with the shrimp distribution of figure 8.

Now applying the same procedure discussed above, if the shrimp school of same size is in the end-fire region, the common area of contribution of one vertical and two horizontal pairs is shown in Figure 13

The common area of contribution of figure 13 for all hydrophone pairs shows that there is a circular school of shrimps



(a)

(b)

Fig. 11. (a) and (b) represent the cross-correlation of direct signals recorded at two horizontal hydrophones along y axis and the contributing area to the correlation peaks respectively assuming no shrimp in the end-fire region

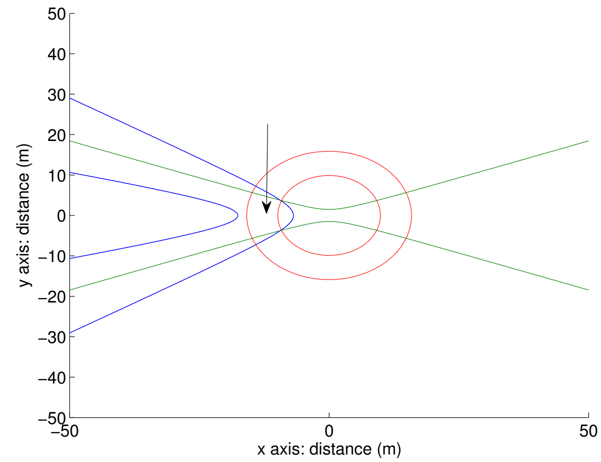


Fig. 12. The common contributing area to the correlation peaks for three hydrophone pairs when shrimp school is not in the end-fire region

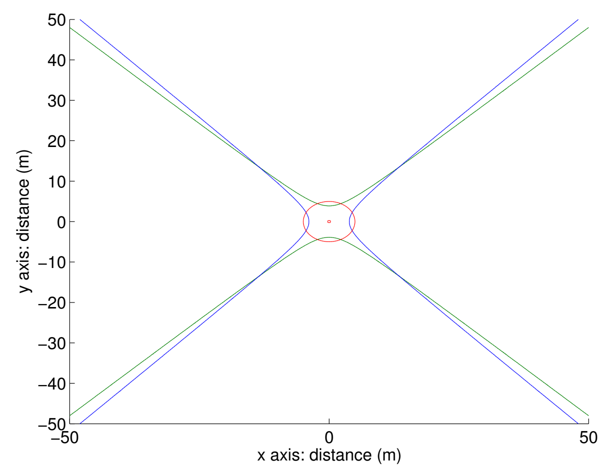


Fig. 13. The common contributing area to the correlation peaks for three hydrophone pairs when a shrimp school is in the end-fire region

centred at the end-fire region and the diameter of the shrimp school is about 5 m. This estimation of the location of the shrimps closely agrees with the distribution of the shrimps.

4. EXPERIMENTAL RESULTS

To estimate the location of shrimps, an experiment is conducted at Jervis Bay near Huskisson, NSW, Australia on 27^{th} of October 2012. An array of four hydrophones as shown in Figure 14 is deployed in a rocky bottom area of about 10m depth to record the sounds produced by shrimps where separation of hydrophones in both vertical and horizontal pairs is 0.5m.

Even though a 4-hydrophone array of figure 3 having two horizontal pairs and one vertical pair of hydrophones is expected to give fully unambiguous estimation, the array shown in figure 14 is used in this shrimp localisation experiment. This is because of the simplicity of the design and available equipments to build the array. Left and right hydrophones of the array are denoted as S_1 and S_3 and top and bottom hydrophones of the array are denoted as S_2 and S_4 respectively. The array is deployed at 2.5 m underneath the surface of ocean, where the seabed is rocky and the depth is about 15 m. The ocean ambient noise generated in the ocean

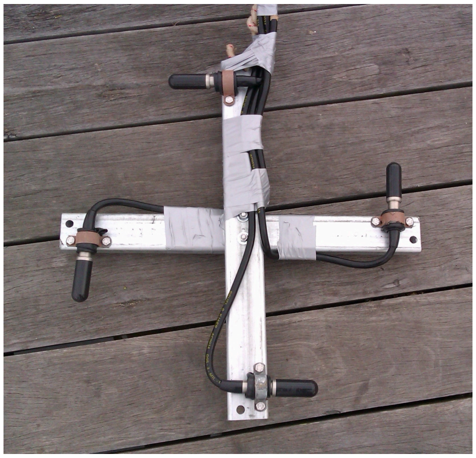


Fig. 14. A four hydrophone array for shrimp detection

is recorded by the hydrophones at the sampling rate of 192 ksps, where the wind generated surface noise and the shrimp sounds are the dominant sources. Since in this experiment we are mostly interested on the clicks generated by the shrimps, a band pass filter of cutoff frequencies 5 kHz and 50 kHz is applied to the recorded ambient noise fields to get rid of most of the surface generated noises and shipping noises. The filtered noise field recorded at hydrophone S_1 is shown in figure 15.

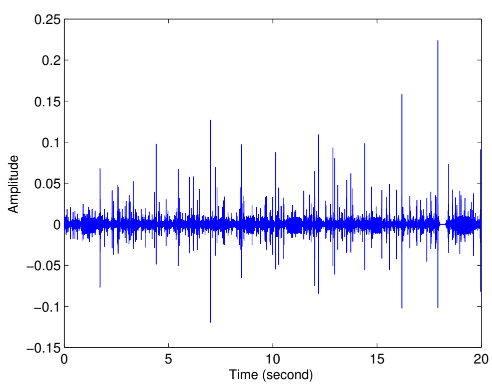
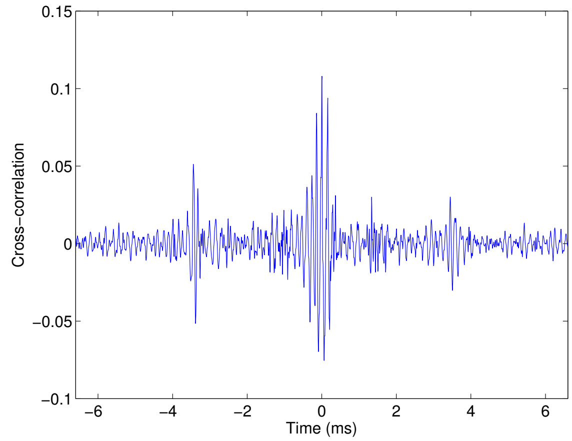


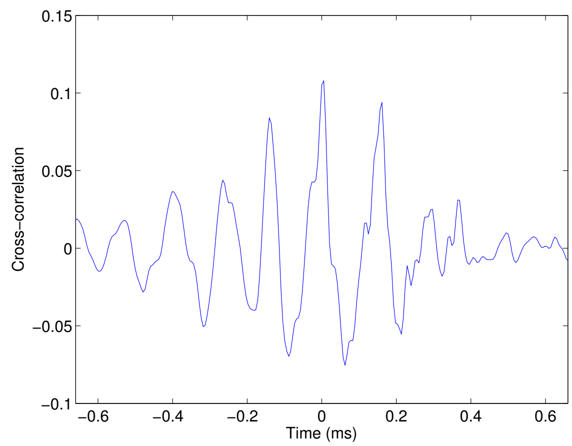
Fig. 15. Filtered (5kHz-50kHz) noise fields recorded at S_1 hydrophone

Figure 15 shows evidence of lots of shrimp clicks present in the recorded noise field. The cross-correlation between the filtered(5kHz-50kHz) and equalised noise fields at two horizontal hydrophones S_1 and S_3 is shown in figure 16.

Since the two horizontal hydrophones are at about 2.5 m depth, signals coming from just below the hydrophones would produce a correlation peak at about 3.33 ms from the centre. This peak would arise from the cross-correlation of the direct



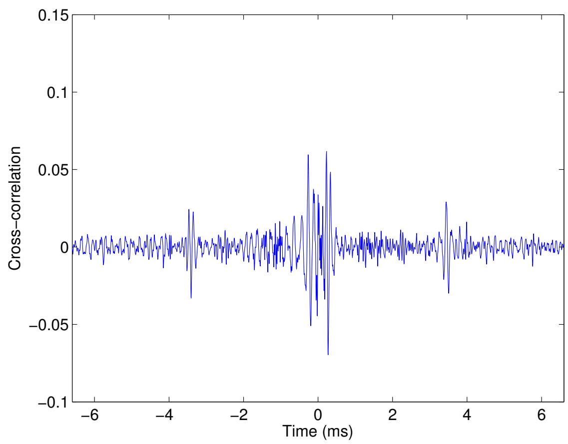
(a) Cross-correlation between noise fields



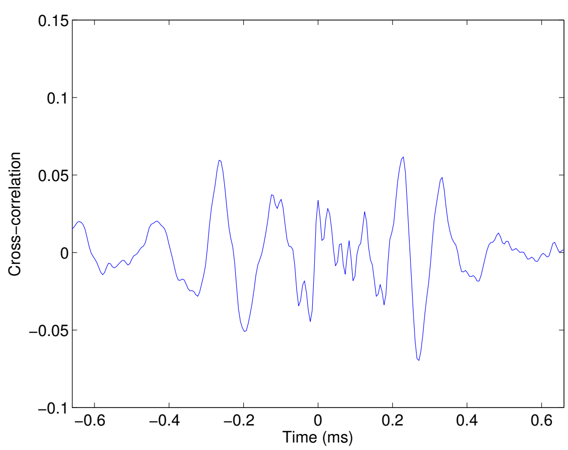
(b) Horizontal zoom of figure 16(a)

Fig. 16. Cross-correlation of the filtered (5kHz-50kHz) noise fields recorded at two horizontal hydrophones S_1 and S_3 after equalisation

signal at one hydrophone and the surface return at other. Figure 16(a) shows that two correlation peaks are generated at about 3.33 ms from the correlation centre, which says that a large amount of shrimps are present on the seabed underneath the array. These two peaks help to detect the shrimp in the place of experiment, because they are generated only for the noises coming from the seabed and the shrimps also lie on the seabed. The cross-correlation between the direct signals contributes peaks within 0.33 ms from the correlation centre. The cross-correlation between the reflected signals also contributes in the same range, but is negligible in power compared to the direct paths because of the large spreading loss and reflection loss of the bottom reflected signal. The centre portion of the correlation of figure 16(a) has been zoomed in for the clear visibility of the cross-correlation between the direct signals and shown in figure 16(b). The cross-correlation shown in figure 16(b) is expected to give more detailed information about the position of the shrimps as described in the theory. The strongest correlation peak in the cross-correlation between the direct signals at two horizontal hydrophones is generated at the centre of the correlation. This peak says that the largest number of shrimps are located along the perpendicular line of the line connecting two horizontal hydrophones. Now to estimate, from which portion of the perpendicular line the shrimp sounds are coming, the cross-correlation between the noise fields recorded at two vertically separated hydrophones is performed. The cross-correlation between the noise fields recorded at vertical hydrophones S_2 and S_4 after equalisation is shown in figure 17.



(a) Cross-correlation between noise fields



(b) Horizontal zoom of figure 17(a)

Fig. 17. Cross-correlation between the filtered (5kHz-50kHz) noise fields recorded at two vertical hydrophones S_2 and S_4 after equalisation

The correlation peaks due to the cross-correlation between the direct path signal at one of the vertical hydrophones and reflected signal at the other hydrophone is also generated at about 3.33 ms away from the correlation centre as shown in figure 17(a). According to the theory, these two peaks also state that a large amount of shrimps are located underneath the array. The cross-correlation between the direct signals at hydrophones S_2 and S_4 is shown in figure 17(b). In figure 17(b), the strongest correlation peak is generated at about 0.3 ms away from the correlation centre which also says that a large number of shrimp sounds are coming from underneath the array.

If a large number of shrimps are located underneath the array, both the cross-correlation between direct and reflected signals and the cross-correlation between direct signals give an unambiguous estimate. However, if the strongest sounds are coming from the shrimps located away from the endfire region, the cross-correlation between direct and the reflected signals does not give the exact position and only the range. The cross-correlation between the direct signals at the two horizontal hydrophones and the two vertical hydrophones gives more detail information about the location of the shrimps irrespective of where the most of the shrimps are located.

Estimation of the location and the density of the shrimps may be problematic in some circumstances. One of these cases occurs when a large number of shrimps produce very frequent clicks. If the clicks are so frequent that the correlation peaks due to the cross-correlation of individual clicks are generated within the area where the correlation peaks due to the cross-correlation between direct and reflected signals and the cross-correlation between the direct signals at two hydrophones are generated. Another issue that might cause problems when other marine animals such as dolphins or whales make strong sounds compared to the shrimp clicks from the areas underneath the array. Estimation of the shrimps in these circumstances need further investigation.

5. CONCLUSIONS

In this paper, it is shown theoretically, numerically and experimentally that the cross-correlation between the shrimp dominated OANs at shallow Australian water can be used in the passive estimation of the location and the density of the shrimps or school of shrimps. Directional ambiguity in the estimation of the shrimp localisation is also analysed, leading to the design of a new type of array to resolve the ambiguity. In the new non-linear array, two pairs of horizontal hydrophones and one pair of vertical hydrophones are used. The previously proposed techniques of estimating shrimp locations use a linear array, which needs to be placed in one side the shrimp schools to resolve the ambiguity in the estimation of the location of the schools. However, in the new technique proposed in this paper, the array can be placed anywhere even inside the shrimp dominated area and the new array geometry helps to resolve the directional ambiguity in the localisation.

6. REFERENCES

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